

Strength estimation model for high-strength concrete incorporating metakaolin and silica fume

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Speed is one of the most crucial factors in determining the profitability of a construction project. Hence, more often than not, contractors are pressured to remove structural formwork in the shortest time possible; that is, immediately after the concrete is assumed to have gained sufficient strength to safely support its self-weight and additional loads from construction machineries. However, this practice can compromise safety, and catastrophic construction failures resulting from inaccurate estimates of in situ concrete strength are well documented. This gives rise to increased emphasis on the need for accurate concrete strength estimation.

Concrete gains strength gradually as a result of chemical reaction between cement and water; for a specific concrete mixture, strength at any age is related to the degree of hydration. Since the rate of hydration is a function of temperature, the strength development of a given concrete depends on its time–temperature history, assuming that sufficient moisture is available for hydration. This is the basis of the maturity concept, which was developed in the early 1950s to assess the development of in situ concrete strength during construction. According to this concept, strength of hardening concrete can be estimated at any age by computing the “maturity” based on the temperature–time history of the concrete [1]. The maturity rule proposed by Saul [2] states that specimens of concrete of the same mixture will have equal strengths if they have equal maturity values, although their temperature histories may differ.

By using a maturity function, the measured temperature history of the concrete is converted to a numerical index, which indicates the extent of strength development. Concrete strength is then estimated based upon the measured maturity index and the strength maturity relationship for that particular concrete mixture [3]. ASTM C 1074 [4] provides a standard practice for using maturity to estimate concrete strength.

In the case of high-performance concrete, however, strength development is more complex in nature due to the combined physiochemical effects of pozzolans in concrete. The physical influence is in the refinement of pore structure of the cement paste, while the chemical phase consists of the pozzolanic reaction, which replaces C-H crystals with cementitious C-S-H gel. However, partial replacement of cement in concrete by pozzolans can produce an immediate dilution effect, which will cause early concrete strength to reduce in approximate proportion to the degree of replacement [5]. In this article, an investigation is carried out to relate the strength of concrete mixtures made with pozzolans to the strength of the ordinary Portland cement (OPC) control mixture. The parameters involved in this model are the pozzolanic and dilution factors, which depend on the amount of pozzolanic material present in the mixture. The key feature of this model is in its simplicity; since other factors relating to water/cementitious materials ratio (w/cm), age, cement content, and temperature can be disregarded because both the pozzolanic and control mixtures have similar material proportions and are assumed to have undergone the same curing history.

2. Experimental procedure

2.1. Materials and mixture proportions

OPC (ASTM Type I), commercial densified silica fume (SF), and laboratory-produced metakaolin (MK) were used. MK was obtained by calcination of raw Malaysian kaolin at 700 °C for 7 h, using a rotary electric furnace.

Physical properties and chemical composition of the cementitious materials are given in [Tables 1 and 2](#), respectively. The coarse aggregate was crushed granite with 10-mm nominal maximum size, and the fine aggregate was a medium-graded (BS 882: 1992) siliceous sand. Specific gravities for the coarse and fine aggregate were 2.57 and 2.65, respectively. A polycarboxylic ether-based superplasticizer (SP) with 20% solids and specific gravity of 1.05 was used. Mixing and curing water was taken directly from a tap supply at a temperature of approximately 28 jC.

Twenty-one concrete mixtures were proportioned using the Sherbrooke mix design method [\[6\]](#). The mixtures were divided into Series A, B, and C with free w/cm of 0.27, 0.30, and 0.33, respectively. The pozzolans were used to replace 5%, 10%, and 15% of the mass of cement at each w/cm. Total cementitious materials content for all mixtures was 500 kg/m³, while coarse aggregate content and sand-tototal aggregate ratio were 1050 kg/m³ and 0.4, respectively. SP dosages for Series A, B, and C were 1.8%, 0.8%, and 0.5% by mass of cementitious material content, respectively. Mixing water was adjusted to correct for aggregate absorption and for the additional water brought into mixture from SP. Mixture proportions are summarized in [Table 3](#).

2.2. Mixing and curing

A pan mixer was used. Fine aggregate and cement were mixed first, followed by the addition of pozzolan and coarse aggregate. Materials were mixed dry for a period of 1 1/2 min. Three quarters of the mixing water was then added while the materials were being mixed, followed by SP, and finally the remaining water. Wet mixing was continued for a total period of 5 min.

Cube specimens were moulded using 100_100-mm steel moulds and compacted in three uniform layers by means of vibrating tables. The amount of vibration required

to ensure good compaction was adjusted based on the Vebe time of the fresh concrete. Forty cube specimens were prepared for each mixture. After casting, specimens were covered with wet burlap to prevent moisture loss and were stored in the laboratory at ambient temperature of 28 °C and 75% relative humidity. After 24 h, specimens were demoulded and cured in a water tank, under room temperature until the day of testing.

2.3. Strength testing

Compressive strength tests (BS 1881: Part 103: 1983) were performed on 100-mm cube specimens at ages of 1, 3, 7, 28, 56, 90, and 180 days, using a 2000-kN compression testing machine with a digital load display. Testing was conducted immediately after specimens were removed from the curing tank. Specimen dimensions and masses were measured to check for any gross fabrication error. While waiting to be tested, specimens were covered with wet burlap to maintain a wet condition. At least three specimens were tested at each age to compute the average strength. Additional specimens were tested if any individual strength result deviated substantially from the mean. A new average was computed based on the three closest strength results.

3. Test results

3.1. Data analysis

The average coefficient of variation for all strength results was found to be approximately 1%. This low variation indicates reliability of the results, which is attributable to a good control of the materials used and adherence to standard concreting and testing procedures. [Fig. 1](#) shows the strength of the MK and SF mixtures plotted against the strength of the control mixture. It is observed that the strength of a mixture with pozzolan is almost a linear function of the strength of the control mixture. Subsequently, the best-fit linear equation for each case was determined using simple regression analysis based on least squares

method. The coefficient of determination, r^2 , for each linear equation was found to be very close to unity, indicating that the linear model is a good description for the relationship between the two variables. The lowest r^2 value obtained from the regression analysis was .96. A total of 147 sets of data were used in the analysis.

The r^2 value provides an index of the degree to which a set of plotted points clusters about the regression line. The closer the points fall along the regression line, the larger the value of r^2 and the greater the proportion of the total sum of squares accounted for by the linear regression of Y on X [7]. However, to be reasonably confident that the two variables are, in fact, related, further statistical analysis is required. A confidence test was performed to investigate whether a significant direct relationship exists between the strength of a pozzolanic mixture and its control, the results of which are shown in Table 4. Standard errors are estimates of uncertainties in the regression coefficients. The t statistic tests the null hypothesis that the regression coefficient is 0, that is, the independent variable does not contribute to estimating the dependent variable while P value is the probability of falsely rejecting the null hypothesis. From the results, it is concluded that the relationship is significant at 95% confidence.

Another statistical tool to evaluate the suitability of the linear model is by observing residuals plotted as a function of the control strength. Residual plot is a standard tool used to diagnose nonconstant variance, curvature, and outliers [8]. If the relationship between X and Y is linear and if the various assumptions made in a regression analysis are true, then a plot of residuals against the values of X will show no apparent trend or pattern with changes in X [9]. Fig. 2 is a plot of standardised residuals against control strength for all mixtures. Standardised residual is the raw residual (the difference between the estimated and observed values) divided by the standard error of the estimate, which is a measure of the actual variability about the regression plane

of the underlying population. If the residuals are normally distributed about the regression, 95% of the standardised residuals should lie between -2 and $+2$ and 99% between -2.5 and $+2.5$ [10]. From Fig. 2, almost 100% of the

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